Numerical Simulations of Energetic Internal Waves in Irregular Bathymetries

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LONG-TERM GOAL

My long term goals are to develop validated numerical models suitable for detailed, process oriented studies, to apply these models to a broad class of oceanographically relevant flows and to use the results of these studies to develop simple conceptual models with predictive capability.

OBJECTIVES

The objective of this study is to better understand the effects of mixing and dissipation in hydraulically controlled flows, in particular, the implications of these processes for volume and tracer transport. A specific objective is to understand the processes determining the features observed in the vicinity of the central contraction in the Bosphorus Strait. A secondary objective is to extend the range of problems amenable to process-oriented numerical simulations by enhancing the capabilities of the model developed in this project. The extended model will then be used to undertake a series of process-oriented studies of stratified flow interacting with irregular topography.

APPROACH

This study is a collaborative effort with Dr. Harvey Seim at the Skidaway Institute of Oceanography. Our approach is to develop and apply a three-dimensional LES model for continuously stratified exchange flow through a contracting channel. A series of "lock-exchange" problems were formulated and run with sufficient resolution to capture the formation of interfacial instabilities. The numerical results are compared with predictions based on inviscid two-layer hydraulics and with observed flows in Gibraltar and the Bosphorus. In FY99 a series of parallel laboratory/numerical experiments have being conducted to exercise and test the numerical model under a variety of flow conditions. These studies are collaborative with Dr. Greg Ivey and students at the Centre for Water Research, University of Western Australia.

WORK COMPLETED

One of the primary goals of my FY98-FY99 effort was to modify the numerical model used in the study of exchange flow through contracting channels to simulate stratified flow over variable bottom topography. This has been accomplished and the resulting model is now available. The numerical tool developed is most appropriate for process oriented studies involving interactions between internal waves and topography. To summarize briefly, the numerical model is unique in that it provides approximate solutions to the non-hydrostatic primitive equations for incompressible, Boussinesq flow incorporating the following features:

(a) a boundary-fitting curvilinear grid that can be clustered as resolution requirements dictate
(b) relatively high-order numerical methods (4^{th} order in space, third order in time)
(c) a multi-grid based iterative scheme for solving the transformed pressure equationexecution in either DNS mode (i.e. as a direct numerical simulation resolving the dissipative scales) at low to moderate Reynolds numbers or LES mode (i.e. resolving the energy containing scales and parameterizing sub-grid-scale effects via a Smagorinsky-like closure hypothesis)
(d) runtime specification of a relatively wide array of boundary conditions, e.g. open boundaries, free- and no-slip walls, specified scalar values or fluxes
(e) the code itself has been validated via several test cases for which analytical solutions are known, comparison against laboratory experiments and comparison against approximate analytical solutions when exact solutions are unavailable.

A manuscript documenting the numerical methodology, the validation procedure and a few sample applications has been accepted for publication in the *International Journal for Numerical Methods in Fluids*. In addition to the numerical development discussed within the *IJNMF* paper, the grid clustering scheme has recently been modified and improved. It is now much easier to use and provides the user with more control and flexibility. While the underlying capability was always there, it was clumsy and difficult to control and hence was used only in simple situations. This small extension has proven to be of enormous practical utility.

A manuscript (Winters and Seim, 2000) discussing the role of mixing and dissipation in hydraulically controlled exchange flows through a contraction has now been accepted for publication in the *Journal of Fluid Mechanics*. Further work in this area has focused on the idea that there are two natural limits to exchange flow problems. The first is one where inertia and buoyancy forces are dominant and mixing and dissipation are negligible in comparison. This is the limit where the ideas, assumptions and results of classical two-layer hydraulics are valid. A second limit occurs when vertical mixing is so intense that inertia is no longer important, stratification is largely horizontal and the flow is governed by a balance between diffusion and buoyancy. CWR graduate student Andy Hogg, jointly supervised by Winters and Ivey, has begun to explore the regime between these limits using the numerical code developed for the Winters and Seim (2000) study. This work has progressed rapidly and a manuscript has been written and is currently under internal review.

A series of initial simulations of wave breaking at a sloping boundary have also been made. In these simulations, a solitary wave of depression travels along a thin pycnocline toward a sloping bed. The wave breaks at the boundary and mixed fluid is ejected from the boundary layer to the interior of the basin. At issue is the mixing and, in particular, the adjustment of the flow after the mixing occurs. The numerical simulation has been set up to match approximately (limitations due to grid orthogonality prevent an exact match) the laboratory configuration of Michallet and Ivey (1998). Dye visualizations, instantaneous velocity fields obtained from PIV techniques, displacement time series and estimates of mixing efficiency are available from the laboratory study for comparison. Initial comparisons of the velocity field, in particular the convergence of up- and down-slope boundary jets are encouraging. Recent attempts to refine these initial simulations and run them at high enough resolution to resolve the mixing and dissipation have been unsuccessful. The problems have been diagnosed and stem from round-off errors associated with the large dynamic range seen in the various grid metrics and coefficients appearing in the transformed equation for pressure. Recognizing the problem, a simple change in the way the coordinate transformations are defined will alleviate much of the problem. Parallelization: The key elements of the code, i.e. the differentiation schemes and the elliptic solver for pressure have been parallelized for execution under MPI (Message Passing Interface). These elements have been extensively tested on a small workstation cluster of DEC Alpha machines connected via a dedicated switch and 100 Mbs ethernet. The algorithm as a whole has also been rewritten for MPI but to date has only been cursorily tested.

RESULTS

In the past year, the newly enhanced numerical model has been applied in process-based studies of several different problems of oceanographic relevance. Though much of this year's effort has been focused on configuring, testing and running the model for these problems, scientific results are now beginning to emerge from each of the studies.

Exchange flow through a contracting channel:
We have found that the type of exchange flow is strongly dependent upon the strength of vertical mixing in the region near the contraction. Mixing can be induced either internally, e.g. via billowing instabilities associated with high shear, or externally, e.g. by tides or winds in shallow systems. A set of numerical experiments were designed and conducted to quantify how vertical mixing, whatever its origin, alters the volumetric and tracer fluxes through the contraction. These experiments would be difficult to achieve in the laboratory, as it is difficult to control and measure the amount of vertical mixing. However, using the numerical model we are able to conduct idealized experiments where the amount of mixing is treated as a free parameter. Numerical results indicate a smooth and predictable transition between two idealized limits: hydraulic solutions when mixing is small and buoyancy-diffusion when it is large. This approach has resulted in a unified framework for a large class of geophysically relevant exchange flows.

Submaximal exchange over a sill:
We consider a stratified basin separated from a large reservoir by a topographic sill. The reservoir is subject to a negative buoyancy flux at the surface (e.g. excess evaporation or cooling). The loss of buoyancy results in turbulent convection within the basin and consequently to a lateral density gradient between the basin and the reservoir. The density contrast leads in turn to a lateral exchange flow that is hydraulically controlled at the sill crest. Our interest is in the circulation within semi-enclosed seas and the process of exchange between such water bodies and the world oceans. The research program was begun with a series of laboratory experiments aimed at revealing the basic dynamical features of an idealized sill-enclosed sea that is forced at the surface by a net loss of buoyancy. We thus modeled, in an idealized manner, the flow in water bodies such as the Mediterranean and Red Seas. Following this we have initiated a numerical study that builds on the laboratory findings by permitting us to extend the parameter range of the experiments. The high temporal and spatial high-resolution of the numerical experiments has also allowed us to gain a deeper understanding of the detailed mechanisms which control the internal dynamics of the basin and the exchange flow over the sill. In addition, the flexible boundary conditions built into the numerical algorithm allow the specification of time-dependent convective forcing and we are thus able to simulate the response characteristics of a seasonally forced sea. Figures 1 and 2 below give an indication of the flows under study and demonstrate the validity of the numerical approach.

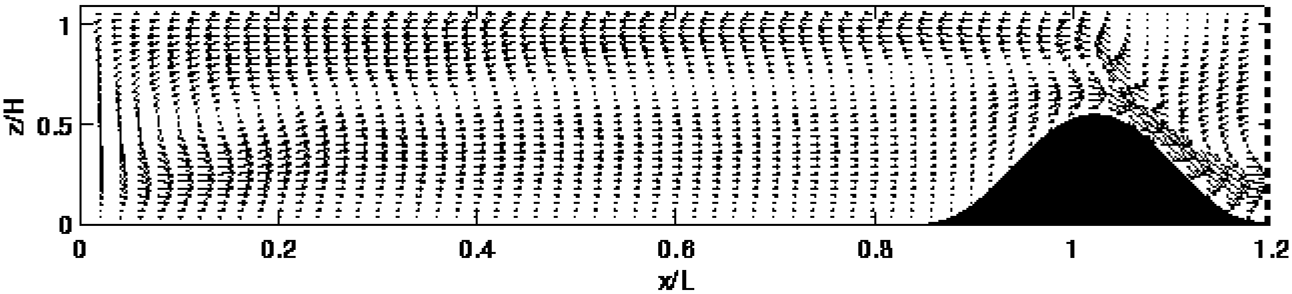

Figure 1: Convectively driven mean flow at steady-state. Surface forcing is imposed for 0<x/L<1. Open boundary at right edge separates the basin from a large reservoir.

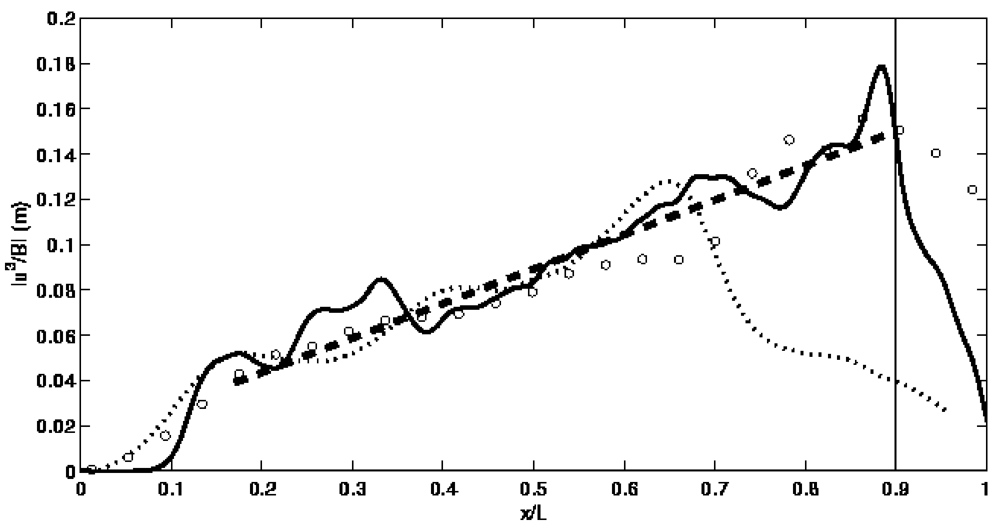

Figure2: Steady-state comparison of scaled along-channel velocity profiles between laboratory experiment (dots), numerical simulation of flow in short basin (dotted line) and numerical simulation of long basin (solid line). Away from the left endwall and to the left of the sill, both the laboratory and the numerical experiments obey the same scaling law.

Wind-driven coastal upwelling

In this problem, an along-shore surface current is forced in a continuously stratified fluid over a sloping bottom. The direction of the forced flow is such that offshore Ekman transport and coastal upwelling develops. A series of nearly 50 laboratory runs were made on a rotating table by Ivey and co-workers at the University of Western Australia. A complementary suite of approximately 15 numerical simulations was also conducted. The numerical experiments were designed to (a) verify the numerical techniques, (b) extend the feasible parameter range (particularly to increase N/f) and (c) to provide details relating to instabilities in the Ekman layer, the formation of a density front and time dependence of the flows. Good agreement between laboratory and numerical experiments has been observed across a relatively wide parameter range and a dynamical understanding of the observed features and scales of the flows has begun to emerge. In addition to variable topography, these simulations require grid clustering (to concentrate resolution near the upper surface and resolve instabilities of the Ekman layer), non-hydrostatic and rotational effects. This study is ongoing in collaboration with Greg Ivey at UWA and Mike Coates at Deakin University. Both of these researchers and laboratory costs are funded by the Australian Research Council (ARC).

IMPACT/APPLICATION

A quantitative understanding of the role of dissipation and mixing in exchange flows, even for idealized problems, may lead to a deeper understanding of the dynamics of naturally occurring flows, particularly those in which dissipation and mixing are clearly significant dynamical processes. A better understanding of the importance and nature of near surface instabilities and the dependence of the surface signatures in upwelling flows on ambient stratification, slope angle, wind speed and latitude will lead to firmer quantitative predictions of upwelling regimes, particularly for transient or unsteady upwelling regimes. Building a database of simulations that have been quantitatively compared against laboratory experiment will hopefully lead to an increased appreciation and use of these types of tools for process oriented experiments.

TRANSITIONS

The numerical models developed for this project are currently being used by three Ph.D. students supervised jointly by Dr. Greg Ivey and myself at the Centre for Water Research, University of Western Australia. Tim Finnigan is investigating exchange flow over a sill driven by spatially localized surface buoyancy flux. Andy Hogg is investigating the role of instabilities and mixing in determining volumetric and tracer transport in exchange flows through contracting channels. Alexander Cuneo is studying rotating exchange flows. The first two studies are based on combined numerical/laboratory experimental approach while the third will be primarily numerical.

Mike Coates at Deakin University is also using the code and collaborating on a laboratory-numerical investigation of wind-driven coastal upwelling.

Don Slinn and Thomas Pierro are also using the model to investigate turbulent boundary layers at the sea bed over wavy bottom topography (sand ripples). A poster describing the results of this study (Slinn, Pierro and Winters) will be presented at the fall AGU meeting.

The code will be made available to Drs. Pascale Lelong and Tim Dunkerton at NWRA in Bellevue WA for a study of internal waves and potential vorticity generation in flow over undulating topography.

RELATED PROJECTS

The modeling of exchange flows is being undertaken as part of a collaborative study of the Bosphorus with Dr's. Mike Gregg and Harvey Seim.

The numerical experiments on coastal upwelling will be used as a starting point to collaborate with Dr. Eric D'Asaro on Lagrangian characteristics of upwelling flows.

The collaboration with Don Slinn is related to his ONR Young Investigator program.

PUBLICATIONS

Winters, K.B., Seim, H.E. and Finnigan, T. D. Simulation of non-hydrostatic, density-stratified flow in irregular domains. In press, International Journal of Numerical Methods in Fluids 1998.

Winters, K.B. and Seim, H.E. The role of dissipation and mixing in exchange flow through a contracting channel. In press, Journal of Fluid Mechanics 1998.

Winters, K. B. and H. E. Seim, 1998: Exchange Flows Through Contracting Channels: Entrainment And Mixing, *Proceedings of 13th Australasian Fluid Mechanics Conference, Monash University, Melbourne, Australia*

Ivey, G. N., Winters K. B. and I. P. D. De Silva 1998: Turbulent mixing in an internal wave energised benthic boundary layer, *Proceedings of 13th Australasian Fluid Mechanics Conference, Monash University, Melbourne, Australia*

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